A silicon-etched probe for 3-D coordinate measurements with an uncertainty below 0.1 μm

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Abstract

The increasing demand for accurate coordinate measurements on products demands new concepts of probe design. Results of some realised designs will be given. One of the most promising utilises microtechnology and etching in silicon in order to realise the necessary dimensional design with flexure hinges. Microtechnology is also used for the detection system; strain gages are integrated in the probe. Results for two probes will be given and possible future developments will be discussed.

1. Introduction

In both manufacturing and measuring technology an ongoing trend for higher accuracies can be seen. Taniguchi noticed this trend [1] and extrapolated it to the future, well predicting the present state of the art in precision engineering [2]. Especially during the last three decades, advances in IC-technology pushed the state of the art forwards. Also in consumer electronics precision techniques found their way, e.g. in video players, CD and its successor DVD (digital versatile disc), and hard disks.

Together with the increasing precision of products, the need for highly accurate dimensional inspection increases. A Coordinate Measuring Machine (CMM) is often used to accomplish this task. Recently the uncertainty of these machines has entered the sub micrometre regime and further effort is done to decrease it further [3]. Probe systems with 3D accuracy substantially below one micrometre, however, are not available.

The touch trigger probe was introduced by Renishaw in the early seventies. As soon as the stylus is moved from its zero position, the resistance of an electrical circuit is altered. At that moment the scales of the CMM are read. An example of such a probe system is shown in figure 2.

Figure 1. Prediction of accuracy limits in the course of time [1]

Figure 2. Schematics of a touch trigger probe

Measuring or analogue probe systems are measuring the probe ball position continuously. After a surface detection the CMM is stopped and controlled by signals of the probe system to reach a pre-set probing force. This technique leads to a significant decrease of the uncertainty down to $0.5\text{ }\mu\text{m}$. In most commercial analogue probe systems both the measuring system as the suspension of the stylus have a larger mass compared to the touch trigger probe. Therefore the probing speed must be lowered in order to prevent intolerable high forces at the moment of probing. Also the controlling sequence takes some time, so probing is more time-consuming than in the touch trigger case. An example of an often used analogue probe system is shown in figure 3.

Figure 3. Example of an analogue probe system

The goal of this research is to develop a new probe system which is lighter and more accurate than such probe systems.

2. Used suspension

From figure 3 it is evident that the 3 stacked guideways take a lot of mass and space. Looking for an alternative a suspension was designed based on slender rods. A slender rod is here defined as a rod-shaped elastic element which fixes one degree of freedom. The probe is connected to an intermediate body which is suspended to the probe house by three slender rods tangentially touching the intermediate body. This suspension has an equal stiffness for all horizontal probing directions. Because of symmetry, the thermal centre is at the z-axis.

Disadvantages are that due to parasitic translations in the length direction of the rods when they are translated out of the xy-plane, the probe will rotate around the z-axis when moved in vertical direction. Besides this, when the tip is not on the z-axis, it will move over a small distance in x- or y- direction when moved in the z-direction.

Figure 4. Suspension of the probe to its housing by three slender rods

3. Realisation of a 2-D probe

3.1 Angle/displacement measurement using an LGDU

The LDGU (Laser Diode Grating Unit) was designed for use in CD players where it fulfills a threefold task: it generates two feed back signals to focus the laser spot on the disk and to follow the track, and it reads the digital data.

It can be used outside the CD player as a distance and angle measuring device. This is commercially explored by Sensor 95. Experimental results of setups using LDGU's are given in [4]. The LDGU is used in the 2D optical probing system to measure the z-displacement and one of the lateral displacement of the probe.

The frame is taken such that the probe is sensitive for z and x-directions. The set-up is depicted in figure 5.

Figure 5. Basic set-up for the LGDU as a distance sensor

The LGDU detects independently the z-displacement of the mirror and its rotation around the y-axis.

3.2 Mechanical design

A probe-house was designed as to connect mechanically the LGDU, the lenses, the suspension and the electronics to a CMM. As the LGDU produces some heat, a drain for the produced heat was provided. The cross-section of the final design is given in figure 6.

Figure 6. A cross-section of the LDGU probe

3.3 Results

The probe was calibrated for displacements in the z-direction by a calibration set-up based on a laser interferometer system.

The output from the LGDU-electronics (as a voltage) was compared to the displacement measurement by a laser interferometer. The capabilities of the LGDU become clear when we consider the residuals after subtracting a first- or higher order polynomial from the calibration curve.

The residuals are shown in figure 7.

Figure 7. Residuals of the calibration in z -direction of the 2-D probe

The figure shows a smooth non-linearity which can well be described by a third-order polynomial. After removal of this polynomial sharp spiky deviations of a few nm occur. These are caused by multiple reflections of the laser light inside the optical system. Introducing a quarter-waveplate in the optical path reduces these effects.

4. Realisation of a 3-D probe system using piezo resistive strain gages

4.1 Displacement measurements using strain gages

Usually strain gauges are connected to the stressed surface by gluing. Due to this hysteresis may arise which results in uncertainty. By using several evaporation, lithography and etching steps the slender rods, the strain gauges, and their electrical connections can be manufactured in one setup. This technology belongs to the field of Micro System Technology (MST). It enabled integrated fabrication of mechanics, sensors, actuators, and electronics on a micrometre scale. As a spin-off of integrated circuit technology, silicon is used as a substrate.

Calculations showed that the strain gages are best placed at the two ends of the slender rods. The read-out can best be done by a wheatstone-bridge. This is depicted in figure 8.

Figure 8. Strain gauges on a rod in a top and a side view. The moment in the rod in the shown position is indicated. The change of the resistance of the strain gauges is measured in a Wheatstone bridge configuration.

The probe design with these strain gauges becomes then as depicted in figure 9.

Figure 9. Probe design with strain gauges in the slender rods

The x , y and z -coordinates of the probe can be calculated from the strains (displacements) in each rod after calibration.

4.2 Producing the probe by MEMS

The probe is produced by bulk micromachining. The process flow for the micromachining of the MEMS for the probe would be rather extensive, therefore, as a representative example, the etching of bulk silicon to the desired thickness is described

here. Start with a bare silicon $\langle 100 \rangle$ -wafer. The silicon is to be etched by KOH. There are other etchants, but KOH is the most used. Places which should not be etched must be covered by a protective layer, a mask, which is able to resist the etchant. Generally this is done by covering the whole wafer with silicon oxide or silicon nitride, applied by a chemical vapour deposition process (CVD). An oxide layer can also be thermally grown

This is done by placing the wafer in an oxide environment at elevated temperatures (800-1100 °C) for several minutes to several hours. Sometimes water vapour is added to increase the growth rate.}, but this is limited to a thickness of 2 μm , which does not always satisfy because silicon oxide is etched slowly in KOH: the mask might be etched away before the desired amount of silicon is etched. To pattern the mask it is covered by a photoresist. The photoresist is illuminated and developed. The parts of the mask which are not protected by photoresist are etched away by an appropriate etchant. Finally the silicon is etched by KOH. A KOH etch is an example of a wet anisotropic etch, i.e. the etchant is a fluid and the etch rate depends on the crystal direction. In case of KOH there is a deep minimum of the etch rate in $\langle 111 \rangle$ direction and a small one in $\langle 100 \rangle$ direction. This means that, provided the etch time is long enough, the etch pit is bounded by $\{111\}$ and $\{100\}$ planes. All other planes are readily attacked by the KOH and will disappear soon. In principle the $\{111\}$ and $\{100\}$ planes are perfectly flat. This gives the possibility of reducing the thickness of a $\langle 100 \rangle$ wafer. In practice, however, it is not that ideal: the surface is roughened, probably due to the forming of H_2 bubbles which tend to stick to the surface, and hillocks arise depending on the concentration of the KOH solution.

The wiring is a story on its own which is not told here, but we give as a final result a picture of a realised probe.

Figure 10. Picture of the realised probe.

4.4 Results of calibrations of the probe.

The AC impedance of the strain gauge resistors has been tested as a function of the frequency of the applied voltage. This revealed a purely resistive behaviour up to about 40 kHz.

The probe was calibrated in a similar way as described in section 3.3.

We give two examples here: the calibration in the z-direction and a calibration a direction in the x-y plane.

The result of the calibration in the z-direction is depicted in figure 11.

Figure 11. Residuals of the excitation of the bridges as function of the imposed displacement in $[0,0,-1]$ direction after subtracting a best fitting straight line. The rod number is indicated on the right side of the plot. The sensitivities of the bridges for the imposed translation, i.e. the slope of the subtracted line, are 0.3944, 0.3428 and 0.4599 ($\mu V/V$)/nm for rod 1, 2 and 3 respectively.

The figure shows that the output of the bridge is very linear with the displacement; the residuals being in the 10 nm range. Also hysteresis is virtually absent due to the integration of the strain gauges.

A similar figure giving the linearity deviations for a displacement in the x-y plane is given in figure 12.

Figure 12. Residuals of the excitation of the bridges as function of the imposed displacement in the x-y plane after subtracting best fitting straight lines. The rod number is indicated on the right side of the plot. The sensitivities of the bridges for the imposed translation, i.e. the slopes of the subtracted lines, are -0.1177 , 0.1793 , and 0.0837 ($\mu\text{V/V}/\text{nm}$) for rod 1, 2 and 3 respectively.

Here we observe residuals of the order of 30 nm at maximum. Although some interdependence in the 3 directions still has to be figured out, it is evident that we have achieved a unique probe with unprecedented low uncertainties.

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6 References

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